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# Test of $^3\text{He}$ -based neutron polarizers at NIST

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## Abstract

Neutron spin filters based on polarized  $^3\text{He}$  are useful over a wide neutron energy range and have a large angular acceptance among other advantages. Two optical pumping methods, spin-exchange and metastability-exchange, can produce the volume of highly polarized  $^3\text{He}$  gas required for such neutron spin filters. We report a test of polarizers based on each of these two methods on a new cold, monochromatic neutron beam line at the NIST Center for Neutron Research. © 2000 Elsevier Science B.V. All rights reserved.

**Keywords:** Polarized  $^3\text{He}$ ; Neutron; Polarizer; Spin filter

## 1. Introduction and polarizer principles

Neutron polarizers and analyzers have a number of applications in both materials science and fundamental physics. The current methods for polarizing neutrons are either deficient in one or more respects or limited to a small range of neutron energies [1]. A dense volume of sufficiently polarized  $^3\text{He}$  can provide an excellent neutron polarizer that avoids these deficiencies. Examples where polarized  $^3\text{He}$  could be useful include using a  $^3\text{He}$  analyzer for small angle neutron scattering (SANS) [2] which requires large angular acceptance. Neutron beta asymmetry measurements rely on absolute knowledge of the neutron polarization at the 0.1% level. Polarized  $^3\text{He}$  may provide analyzers that achieve

this accuracy without the systematic errors associated with super-mirror analyzers [3,4]. A new determination of the weak nucleon–nucleon coupling constant,  $H_\pi$ , plans to make use of a  $^3\text{He}$  polarizer's broad energy range, angular acceptance, and ability to change the polarization direction without changing static magnetic fields [5].

Polarized  $^3\text{He}$  makes an excellent neutron spin filter because of the large spin dependence of the neutron capture cross section. Because the cross section for the absorption of neutrons parallel to the  $^3\text{He}$  nuclear spin is negligible, a sufficient column density of 100% polarized  $^3\text{He}$  would transmit all of these neutrons and none with the antiparallel spin. The neutron polarization  $P_n$  is given by

$$P_n = \frac{T_+ - T_-}{T_+ + T_-} = \tanh(\sigma(\lambda)N_{\text{He}}LP_{\text{He}}) \quad (1)$$

where  $T_+$  ( $T_-$ ) is the transmission of neutrons with spin parallel (antiparallel) to the  $^3\text{He}$  spin,

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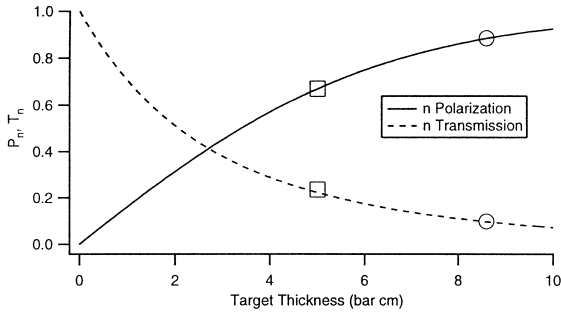


Fig. 1. Neutron polarization  $P_n$  (solid line) and transmission  $T_n$  (dashed line) as a function of target thickness in bar cm at 300 K. The calculation is shown for cold neutrons ( $\lambda = 0.5$  nm) and  $P_{\text{He}} = 0.45$ . The measured polarization and transmission for the spin-exchange (metastable) polarizer are shown by circles (squares).

$N_{\text{He}}$  is the number density of  $^3\text{He}$ ,  $L$  is the length of the  $^3\text{He}$  cell,  $P_{\text{He}}$  is the nuclear polarization of the  $^3\text{He}$ , and the unpolarized neutron absorption cross section is given by  $\sigma(\lambda) = 29\,627\lambda$  b for neutron wavelength  $\lambda$  in nm [6]. The neutron transmission  $T_n$  for all incident neutrons is given by

$$T_n = T_0 \cosh(\sigma(\lambda)N_{\text{He}}LP_{\text{He}}) \quad (2)$$

where  $T_0$  is the transmission for  $P_{\text{He}} = 0$ , given by  $T_0 = T_e \exp(-\sigma(\lambda)N_{\text{He}}L)$ .  $T_e$  accounts for neutron losses in cell windows and other elements in a practical spin filter. For the specific case of cold neutrons ( $\lambda = 0.5$  nm) Fig. 1 shows  $P_n$  and  $T_n$  for  $P_{\text{He}} = 45\%$ , as a function of the filter thickness.

Neutron spin filters can be used equally well as analyzers for polarized neutron beams. For an analyzer under the same conditions, the transmission asymmetry,  $A$ , for 100% polarized incoming neutrons replaces  $P_n$  in Eq. (1) and the flipping ratio is  $F = (1 + A)/(1 - A)$ . If desired, the polarization (or flipping ratio of an analyzer) can be increased at the expense of transmission by using a larger  $^3\text{He}$  target thickness.

For a  $^3\text{He}$  neutron spin filter in a monochromatic beam, the neutron polarization can be determined from measurements of neutron transmission alone [7,3]. For a transmission polarizer in a monochromatic beam, it can be shown that

$$P_n^2 = 1 - \left(\frac{T_0}{T_n}\right)^2. \quad (3)$$

Because  $T_0$  and  $T_n$  are not linear in  $\lambda$ , Eq. (3) is not accurate for spectrum averaged values of  $T_0$  and  $T_n$  obtained with a polychromatic beam.

## 2. Methods

A monochromatic beam line (NG6M) has recently been constructed on the NG6 fundamental physics beam line. The monochromator is a 0.2 cm thick square of pyrolytic graphite crystal, 5.1 cm on a side, placed at roughly  $47^\circ$  to the incident beam. Neutrons with wavelengths satisfying the Bragg condition are diffracted from the (002) crystal plane and out through a hole in the shielding. After a 35 mm  $^6\text{LiF}$  aperture, 8.4 cm of polycrystalline Be at 77 K removes  $\lambda/n$  components of the beam. Be has a Bragg cutoff at 0.47 nm, slightly below the measured average wavelength of 0.496 nm. The monochromatic beam was measured to have a divergence of  $0.5^\circ$  and a flux of  $4.6 \times 10^5 \text{ cm}^{-2} \text{ s}^{-1}$ .

On this new beam we tested polarizers based on two optical pumping methods: spin-exchange [7–10], which is performed directly at high pressure (1–10 bar), and metastability exchange [11–13], in which the gas is polarized at low pressure (1 mbar) and then compressed.

### 2.1. Spin-exchange optical pumping

In the spin-exchange method [14–17], rubidium vapor is polarized by optical pumping of the D1 line. During binary collisions, the hyperfine interaction transfers spin between the polarized rubidium electron and the  $^3\text{He}$  nucleus. The time dependence of the  $^3\text{He}$  polarization is given by

$$P_{\text{He}}(t) = \frac{\gamma_{\text{SE}}P_{\text{Rb}}}{\gamma_{\text{SE}} + \Gamma} [1 - \exp(-(\gamma_{\text{SE}} + \Gamma)t)] \quad (4)$$

where  $P_{\text{Rb}}$  is the rubidium polarization,  $\gamma_{\text{SE}}$  is the spin exchange rate between the rubidium and the  $^3\text{He}$  nuclei, and  $\Gamma$  is the  $^3\text{He}$  spin relaxation rate excluding the rubidium spin exchange. For typical cell temperatures around  $170^\circ\text{C}$ ,  $1/\gamma_{\text{SE}}$  is between 5 and 15 h. It is crucial that  $1/\Gamma$ , the hot spin relaxation time due to mechanisms other than rubidium spin exchange, be many tens of hours. For

convenience, the spin relaxation time is typically measured at room temperature with frozen rubidium, as a good indicator of the hot relaxation time in the absence of rubidium. Since  $\gamma_{\text{SE}}$  varies almost linearly with the rubidium density, the cell temperature can be increased to increase  $\gamma_{\text{SE}}$ , consistent with laser light penetrating the optically thick vapor. For optical pumping with diode arrays, higher-pressure cells (3–10 bar) allow more efficient use of the available broadband laser light, but introduce mechanical constraints on the cell geometry.

The spin exchange cell for this experiment was made from GE180 glass [18], a boron free aluminosilicate glass.<sup>1</sup> The cell is a rounded cylinder about 2.5 cm long and 4 cm in diameter filled with 3.5 bar of  $^3\text{He}$ . The average target thickness was determined to be 8.6 bar cm based on measurements of the neutron transmission through the unpolarized cell and corrected for window transmission. The curved windows used in the current cell design cause a non-uniform target thickness and make it difficult to select a given target thickness. The glass thickness for this sealed cell was measured to be 2.7 mm from the attenuation of  $^{241}\text{Am}$  gamma rays. The measured neutron attenuation length in GE180 glass is 60 mm yielding a neutron transmission through the cell windows of 0.96.

## 2.2. Metastability exchange optical pumping

In the metastability exchange method [19–21], metastable  $^3\text{He}$  atoms are polarized by optical pumping, the resultant electronic polarization is partially transferred to the nuclei by the hyperfine interaction, and the polarization is transferred to ground-state atoms in metastability exchange collisions. In a metastability exchange collision, the incoming metastable atom transfers its atomic

excitation to the incoming ground state atom, resulting in nuclear polarization of the outgoing ground state atom.

Because this method can only be performed at low pressure (1 mbar), the polarized gas must be compressed for our application. A piston compression system, developed at the University of Mainz [22], is currently in use for polarizing neutrons at the Institut Laue-Langevin [4,12]. We have developed a compact compression apparatus based on modifying a commercial diaphragm pump [23]. Using this apparatus, we have obtained 70% preservation of the polarization at gas flow rates comparable to the polarizing rate of the metastable method. We use methods similar to those described in Ref. [22] to preserve the high gas purity required for efficient optical pumping. The apparatus can either be used to fill an initially evacuated storage cell, or a constant pressure can be maintained in the storage cell by continuously leaking gas back to the optical pumping cell.

At low pressure, the  $^3\text{He}$  polarization is accurately determined using the degree of circular polarization of the 668 nm light emitted from the discharge [24,25]. At high pressure, the polarization is measured by free induction decay NMR (FID) [26] using small tip angles. The NMR system is calibrated against the optical method by directly optical pumping low pressure gas in the storage cell, and comparing the optical and NMR signals.

For pure  $^3\text{He}$ , the achievable polarization is limited by the relatively high pressure (3–4 mbar) in the optical pumping cell. To sidestep this current limitation of the apparatus, we have employed a  $^3\text{He}$ : $^4\text{He}$  mixture, for which the optical pumping efficiency is less sensitive to pressure [21]. This method is well-matched to the neutron polarizer application because  $^4\text{He}$  is transparent to neutrons.

## 3. Results

The spin exchange cell was illuminated by 15 W of light from a fiber coupled diode laser array. Due to space constraints, the laser output was split into two counter-propagating beams to illuminate the cell. The  $^3\text{He}$  was polarized along the neutron

<sup>1</sup> Certain trade names and company products are mentioned in the text or identified in an illustration in order to adequately specify the experimental procedure and equipment used. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products are necessarily the best available for the purpose.

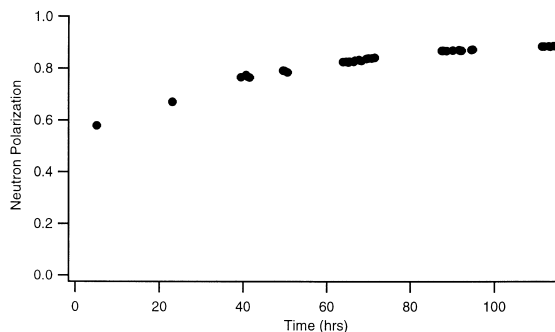


Fig. 2. Neutron polarization as measured by neutron transmission for the spin-exchange experiment.

beam requiring the neutrons to pass through two aluminized silicon wafer mirrors. The mirror transmission was 0.993, and the quartz oven window transmission was 0.86. To maintain circular polarization after the mirror reflections, two mirrors were used for each beam, with  $45^\circ$  reflections in different planes. During the optical pumping, the relative  $^3\text{He}$  polarization was monitored by adiabatic fast passage (AFP) NMR [26].

The spin-exchange apparatus including 2.5 mT (25 G) holding field coils, laser, and oven is on a 75 cm wide slide that can move into and out of the neutron beam. Thin fission chambers were placed up and down stream to measure the neutron transmission. The cell was moved into the beam and allowed to polarize for 5 days. Fig. 2 shows the neutron polarization over the course of the experiment as determined from the measured values of  $T_0$  and  $T_n$  using Eq. (3). The initial polarization time constant was much longer than the expected 10 h, so the oven temperature setting was increased several times with a final temperature of  $170^\circ\text{C}$ . The oven temperature was later found to be very uneven causing large errors in the temperature setting.

At the end of 5 days, the polarization was destroyed. The last polarized transmission measurement,  $T_n = 0.0807$  and the final unpolarized transmission measurement,  $T_0 = 0.0376$ , yield a final neutron polarization of 0.885. Using  $T_0$ ,  $T_n$ , and the thickness of the  $^3\text{He}$  in Eq. (3), the final  $^3\text{He}$  polarization can be inferred to be 45%.

A neutron experiment was then performed using gas polarized by the metastability exchange

method. The gas was accumulated in a storage cell that was immersed in liquid nitrogen to obtain a roughly fourfold increase in the density of the compressed gas. The 4.4 cm diameter, 10 cm long storage cell is constructed from windows made of  $^{10}\text{B}$  depleted Corning 1720 windows diffusion-sealed to a body of normal Corning 1720 glass [27]. The relaxation time of the cell was measured to be 32 h at room temperature and 15 h at 77 K. The  $160\text{ cm}^3$  cell was filled to 0.52 bar at a temperature of 77 K with a  $^3\text{He} : ^4\text{He} = 1 : 3$  gas mixture in 1.3 h, and a  $^3\text{He}$  polarization of 47% was measured using NMR. The cell was transported in a portable solenoid to the beamline where it replaced the spin exchange apparatus. The neutron transmission  $T_n$  was measured to be 0.185, and after destroying the polarization  $T_0$  was measured to be 0.137 yielding a neutron polarization of 0.67. The cell was later evacuated and  $T_e$  was measured to be 0.789, hence, the transmission through the  $^3\text{He}$  alone was 0.235. Using a target thickness of 5.0 bar cm determined from these measurements, the  $^3\text{He}$  polarization at the first  $T_n$  measurement was 47%, consistent with the NMR measurement.

We expect that the dominant source of uncertainty in  $P_n$  is from drifts in the transmission measurements, primarily due to electronics. The relative change in  $T_0$  over five days was 2% which would result in a relative change in the neutron polarization of 0.7%. Since the quoted results for each method were taken within the space of 3 h, we expect that the actual uncertainties are less than this value.

#### 4. Conclusions

We have polarized neutrons using polarized  $^3\text{He}$  produced in two ways, each with its own advantages. With the spin exchange method, we were able to continuously optically pump a cell in the neutron beam. This provided a fairly stable neutron polarizer that required almost no maintenance over several days. This stability would be well suited for long-term experiments such as weak interactions studies. If necessary, cells could also be polarized offline and transported to the neutron beam. Since this experiment, we have produced a 5.5 cm

diameter cell. We are pursuing a 6 cm diameter cell, and a double cell geometry that would be more convenient to polarize in the transverse direction.

In the metastability exchange method, the size, shape, pressure, and orientation of the spin filter cells are more flexible. In addition, the higher polarization rate may be useful for high volume cells and convenient for short-term experiments. Our compression apparatus is small enough to be moved into a neutron beam, but its performance must be improved in recirculation mode and its long-term operation must be tested before it can be used for a lengthy experiment. Both methods are likely to be applicable to practical measurements in the near future.

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